Chapter 5

Simulation of forest hydrology: application of a forest water balance model

5.1 Introduction

In chapter 4 a forest water balance model was presented. The model should be validated with the use of available measurements prior to assessment of climate change impacts. The measurements are preferable to be long-term observations of water fluxes for different forest types and different locations in order to compare the model estimations with the actual water balance under different environmental conditions. Validation is possible for measurements of transpiration, rainfall interception, variation in the soil water content, and CO_2-fluxes by assimilation. To run the model, measurements of meteorological variables are needed as input data, extended with the ambient CO_2 concentration (C_a). Long-term measurements, including CO_2 concentrations and fluxes at canopy scale, only recently became available (e.g., BOREAS, Hall *et al.*, 1995 and NOPEX, Halldin *et al.*,1995). Five data-sets, spread over Western-Europe, were available for validation, but unfortunately they did not contain usable CO_2 or assimilation measurements. The forest water balance model was validated, assuming a constant ambient CO_2 concentration.

Among the five available sets, the data-set of a deciduous forest near Ede in the Netherlands was chosen for the validation of the complete water balance, as it contains the most complete and extensive measurements over a large part of the year. The interception model was also validated on a data-set from HAPEX-MOBILHY (André *et al.*, 1988), consisting of measurements in the coniferous forest near Les Landes in France.

The validation of the model is described in section 5.2. The forest-sites, the measurements and model settings are described in section 5.2.1. In sections 5.2.3 and 5.2.4 the validation of the rainfall interception simulation is described. Results of the transpiration simulation are given in sections 5.2.5 and 5.2.6. Results of the transpiration simulation, using the Leuning-model for stomatal conductance, are compared with those of the Jarvis-Stewart (JS) regression model.

The relative importance of the different model-parameters is further evaluated with a sensitivity analysis, as described in section 5.3. A first assessment of possible changes by climate change in forest hydrology is given, using a combination of estimations of the changes in environmental and tree physiological parameters in a changed forest climate.

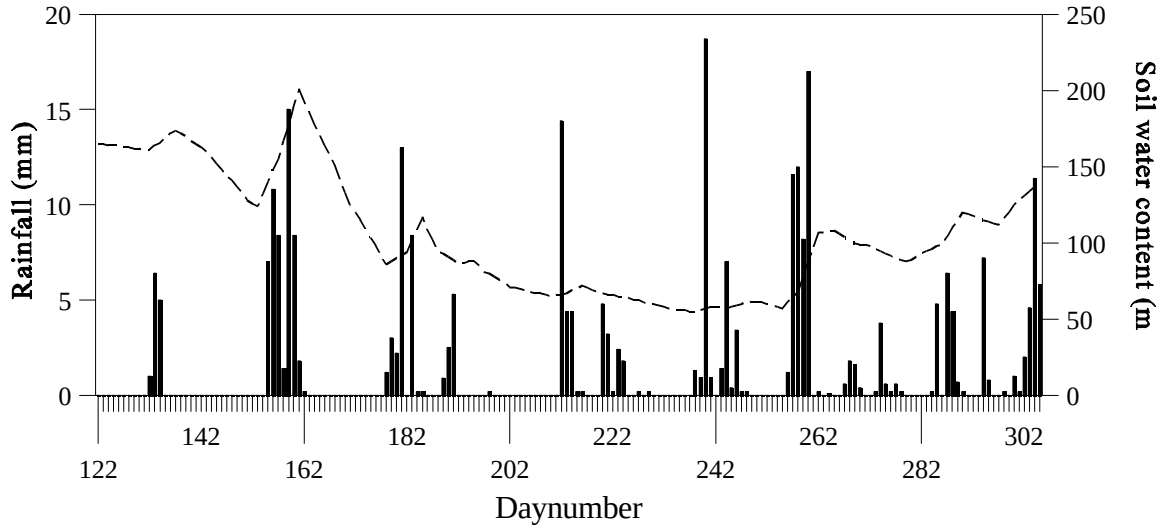

Figure 5.1. Rainfall distribution and soil water content over the simulation period at the Ede location in 1989.

5.2 Model validation

5.2.1 Data

The Ede and Les Landes data-sets both consist of hourly measurements of meteorological variables and fluxes of sensible and latent heat, measured above canopy. Validation of the interception simulation was possible by hourly measurements of precipitation and throughfall. Data on Daily soil water content were available for the Ede location. The soil water content of the Les Landes experimental site was measured (Gash *et al*., 1989), but could not be used in this study.

Ede

The forest site near Ede, the Netherlands (52°02'19" N, 5°45'06" E) consists of red oak (*Quercus rubra*, 92 %), birch (*Betula spec*., 7 %) and douglas fir (*Pseudotsuga menziesii*, 1 %). A detailed water balance study was executed from 1988 until 1990 (Hendriks *et al*., 1990; Ogink-Hendriks, 1995). The homogeneous site of 16 ha is surrounded by coniferous forest of a similar height.

Evaporation was measured with the Bowen ratio method on a scaffolding tower. Instruments and measurements methods are described by Ogink-Hendriks (1995).

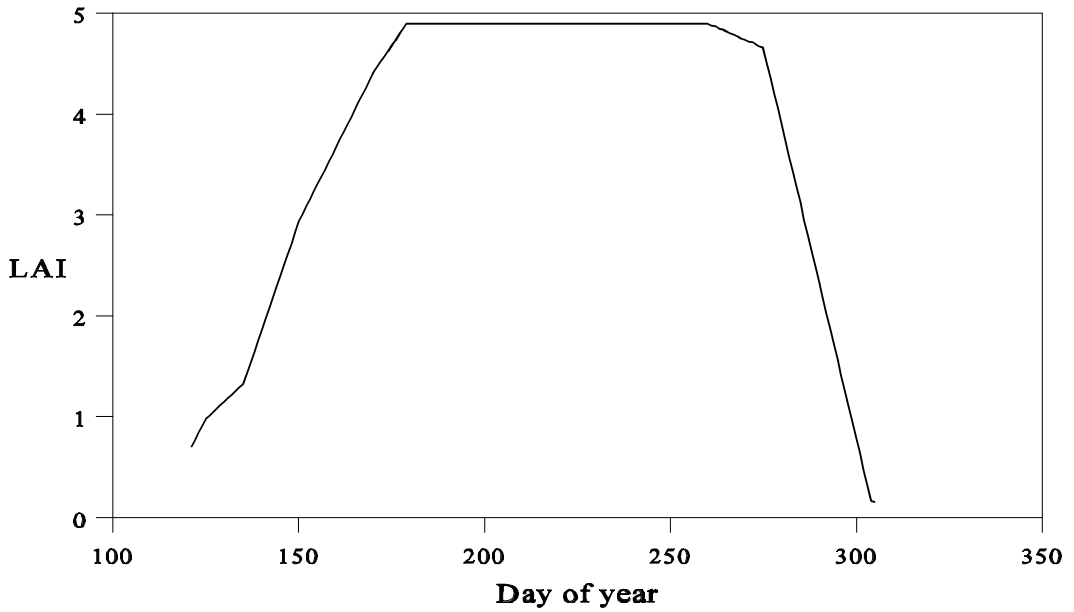

Figure 5.2. LAI distribution of the Ede forest versus the Julian daynumber in 1989.

Rain throughfall was measured in a 25 x 25 m plot, using troughs of 8, 10 and 12 m length and 0.10 m width, resulting in a total catchment area of 3 m^2. Stem flow of six trees was recorded; it was negligible, less than 1 % of the total precipitation during summer. During the leafless period in winter, stem flow was about 4.5 %. Precipitation was measured above the forest site and in a clearing, 400 m west of the measurement site. The measurements of rainfall at both sites agreed most of the time very well, within 2 %, and the measurements above forest were adjusted to the values measured at the clearing, if necessary (Hendriks *et al*., 1990).

Water content of the sandy soil was measured twice a week using capacitive probes in two columns at 9 different depths. The measurements were interpolated to daily values. Ground water level was measured weekly; it varied from 4.3 to 5.2 m below surface, and capillary rise from ground water level could be neglected. Rainfall distribution and soil water content over the year 1989 are shown in figure 5.1.

Maximum leaf area index (LAI_{MAX}) was measured by catchment of the falling leaves at 9 random places. The distribution of LAI over the year was determined with light-interception measurements. The LAI, as a function of the Julian day number for 1989, is shown in figure 5.2 (Hendriks *et al*., 1990).

The meteorological measurements consisted of hourly average values of global radiation, net radiation, wind speed, air temperature, air humidity, leaf wetness and precipitation. The year 1989 was, compared to the normal over the period 1961-1990, relatively dry with warm weather in May and autumn (table 5.1). The month May was very dry, compared to the

Table 5.1. Monthly average temperature and total precipitation at the Ede location in 1989 and the normal 1961-1990. (KNMI, 1992)

	Average Temperature (°C)		Total Precipitation (mm)	
Month	Ede 1989	Normal[1]	Ede 1989	Normal[2]
May	14.2	12.2	12.4	57.1
June	15	15.1	72.4	65.7
July	17.4	16.6	44.8	68.2
Aug	16.7	16.6	47	57.4
Sept	14.9	13.8	68.4	69.0
Oct	11.8	10.2	72.9	76.3
Total	15	14.1	317.9	393.7

[1] KNMI station Deelen 1961-1990

[2] KNMI station Soesterberg 1961-1990

normal. In May (day 120-150) several days exhibited high temperatures with high air humidity deficits and as a consequence the dry and warm weather resulted in high soil moisture deficits (figures 5.1 and 5.3).

Transpiration simulation was possible over 183 days, from day 122 (2nd of May) until day 305 (1st of November); only 135 days had complete meteorological data over all hours. To compare simulated and measured transpiration, data were selected for global radiation (Q_s) above zero and available energy (Q_{AC}) above 20 W m^{-2}, to exclude errors due to condensation and low transpiration. The selection resulted in 1229 hours, divided over 161 days. Simulation of the interception was also possible over the same period, resulting in a simulation of the water balance over the period from 1 May until 31 October 1989.

HAPEX-Les Landes

Les Landes was the forest location in HAPEX-MOBILHY in south-west France (44°5'N, 0°5'W). A description of the micro-meteorological measurements, performed during the experiment is given by André *et al*. (1986), and the site is described by Gash *et al*. (1988, 1989).

Throughfall was measured in a 30 x 30 m plot of Maritime Pine (*Pinus pinaster*) with 22

bottle gauges, relocated every two weeks, and every five minutes by 16 tipping-buckets rain-gauges, which were randomly placed and connected to data loggers. Stem flow, measured for several trees, appeared to be small, and therefore it was neglected. Precipitation was measured above the forest. The results were not significantly different from measurements of rainfall in a forest clearing, 480 m away from the tower (Gash *et al*., 1988).

The period from 8 February until 31 December 1986 has been used for model validation. Total precipitation over this period, with 161 rainy days, was 720 mm (figure 5.4). Most

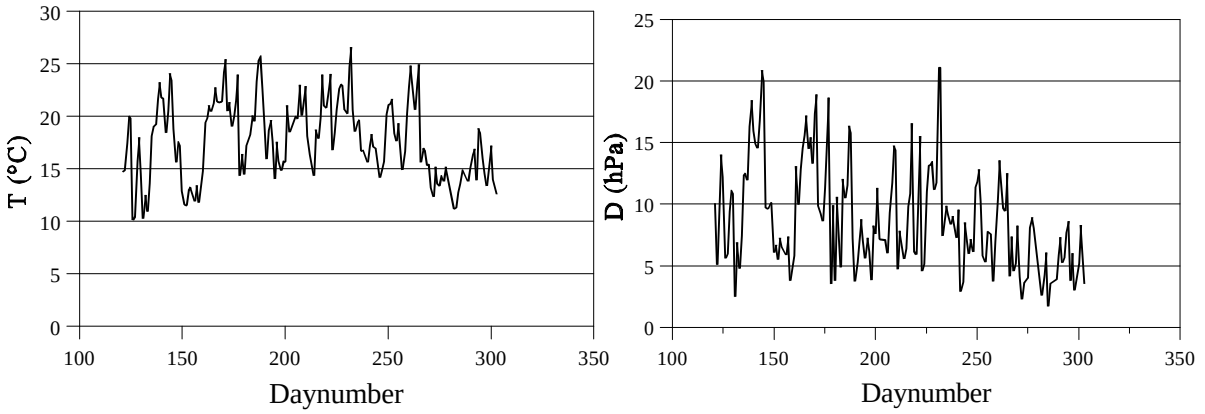

Figure 5.3. Daily average temperature and air humidity deficit, at Ede, 1989.

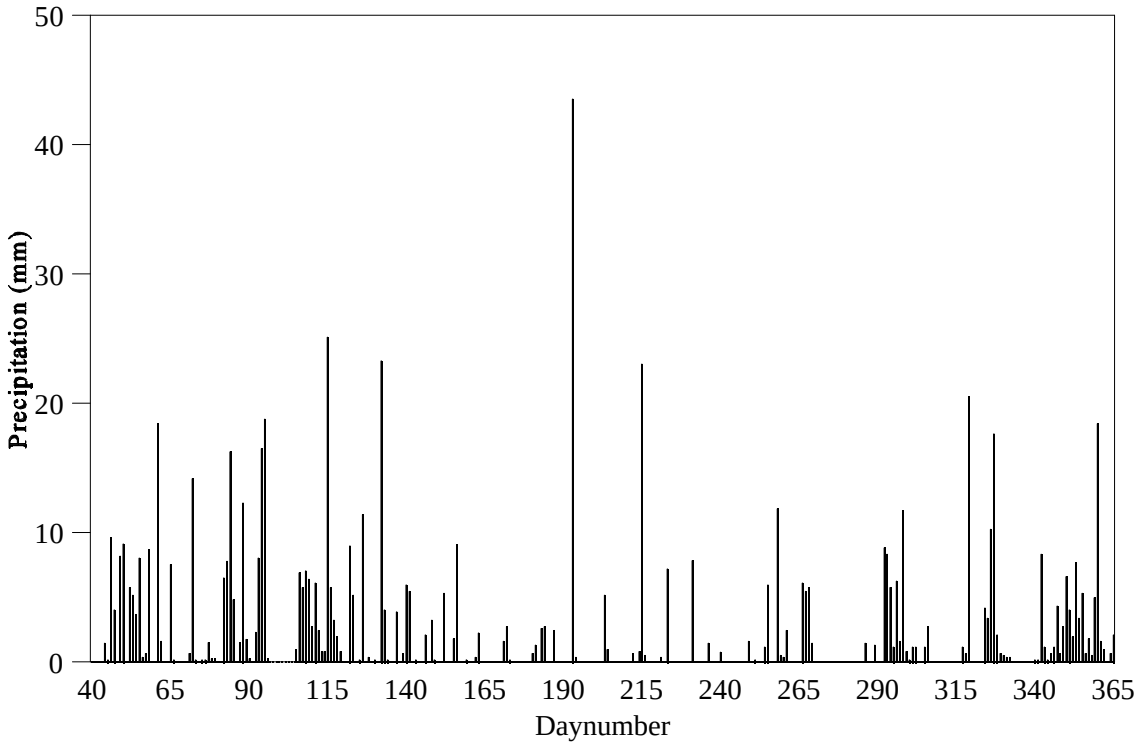

Figure 5.4. Rainfall distribution at the Les Landes location in 1986.

Tabel 5.2. Site characteristics of the Ede and Les Landes locations and model settings for interception simulation.
(s= leaf period, w= leafless period)

	Ede		Les Landes
Measurement year	1989s	1989w	1986
Tree density (tree ha^{-1})	600		430
Mean tree height (h in m)	17.4		20.3
Free Throughfall Coeff (p)	0.31	0.8	0.43
Storage capacity (S in mm)	0.5	0.2	0.26
Zero plane displacement (d in m)	13.05	10.44	15.1
Roughness length momentum ($z_{0,M}$ in m)	1.74		1.9
Roughness length heat ($z_{0,H}$ in m)	0.24		0.26
Height of measurements (Z in m)	22.8		25.9
Number of comparable simulation days	38		86

rainfall fell during spring and towards the end of the year. Complete meteorological measurements of 85 days were available for a comparison of actual and simulated interception values.

5.2.2 Model initialisation

The parameter values for the simulation of rainfall interception were taken from previous studies, using the same data, (Hendriks *et al*., 1990; Lankreijer *et al*., 1993), and they are given in table 5.2.

Transpiration was simulated with two model versions: the assimilation-stomatal conductance (A-g_s) model, based on the model by Leuning (1995), further denoted as the 'Leuning-model' and the regression type model of Jarvis-Stewart, denoted as JS. The

Table 5.3. Parameters of the Leuning-model run on the Ede site, 1989.

a_1	$D_{S,0}$	LAI_{MAX}	θ_{FC}	θ_{MAX}	a_θ	k
10	0.2	4.9	200	142.1	0.11	0.7

Tabel 5.4. Parameter setting Jarvis-Stewart model for Ede, 1989 (Ogink-Hendriks, 1995)

$G_{s,max}$(mm)	a_s	a_{T2}	a_{D4}	a_{D5}	a_θ
51.01	254.1	16.79	0.2305	0.7089	0.0876

parameter values of the assimilation simulation by the A-g_s model were taken from Friend (1995) and they were already described in chapter 4 and in appendix A. The Leuning-model was tuned by the parameters a_1 and $D_{s,0}$, assuming the calculated A to be realistic. The parameters of the Leuning-model are given in table 5.3. The parameters, describing the relation between soil water content and surface conductance, were taken from the study by Ogink-Hendriks (1995). The value for the extinction coefficient k was based on the value given by Jones (1992). Tuning both parameters a_1 and $D_{s,0}$ was performed on selected hourly data with no soil water deficit (θ >100 mm) and a measured evaporation rate not above 2 mm s^{-1}. $D_{s,0}$ was found by use of the fitted function between G_s and D. The parameter a_1 was adapted until the simulated surface conductance was close to the actual surface conductance.

The transpiration simulation results, obtained from the use of the Leuning-model for stomatal conductance, were compared with measured values and with simulation results, obtained by using the G_s model of Jarvis-Stewart. The parameter values for the JS model were taken from the fitting by Ogink-Hendriks (1995) and are summarized in table 5.4. A complete description of the JS model is given in section 3.5.

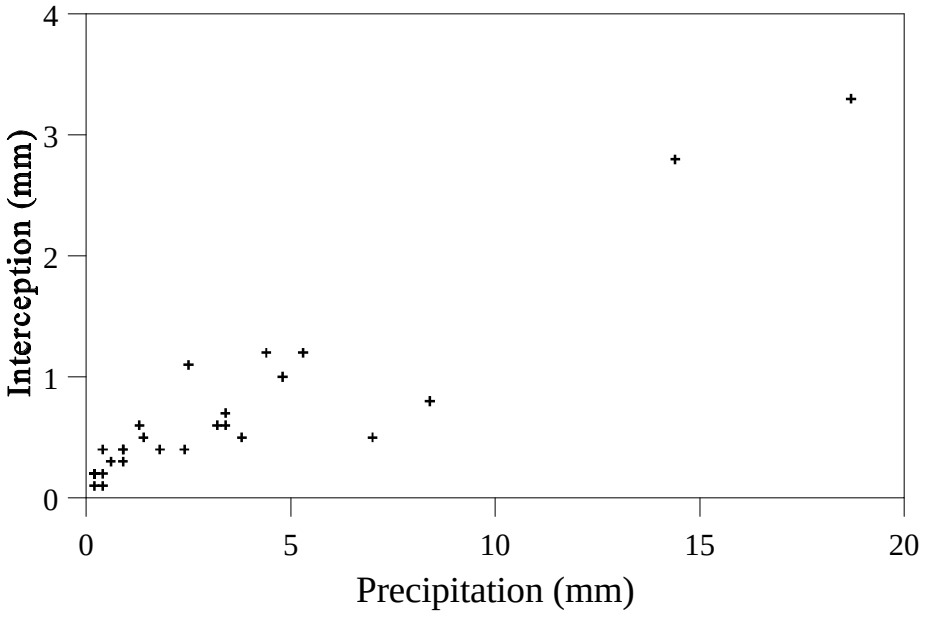

Figure 5.5. Daily total interception versus precipitation for the Ede location (1989).

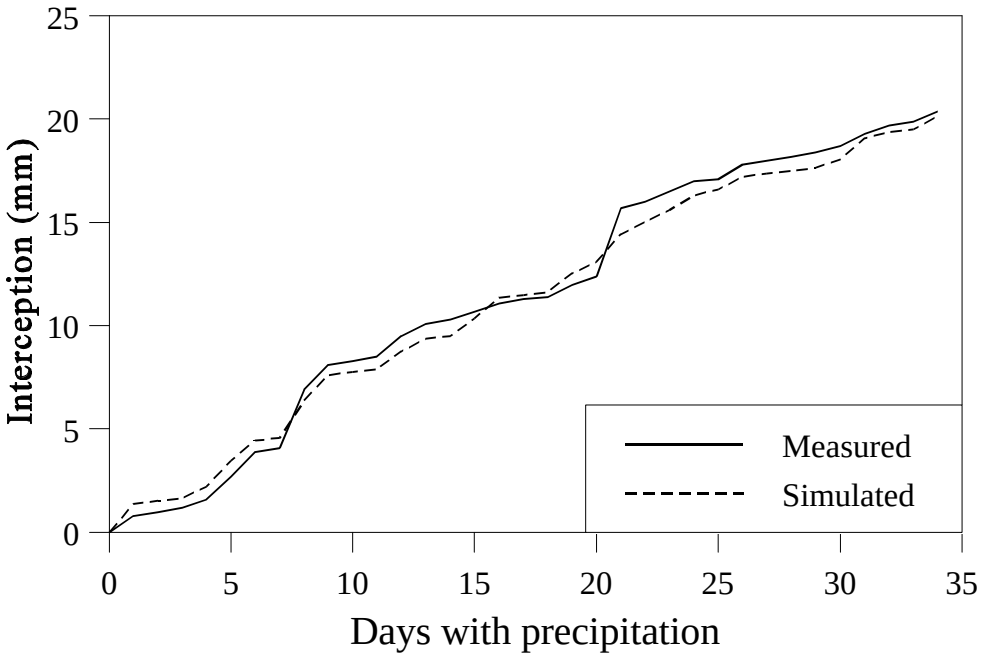

Figure 5.6. Accumulative measured and simulated interception for Ede location.

5.2.3 Simulation of rainfall interception

Ede

Measured rainfall interception was plotted versus precipitation for 34 days (figure 5.5). On some days precipitation and interception were equal and therefore the points near the origin in the graph coincided. According to Hendriks *et al*. (1990), total rainfall over the whole

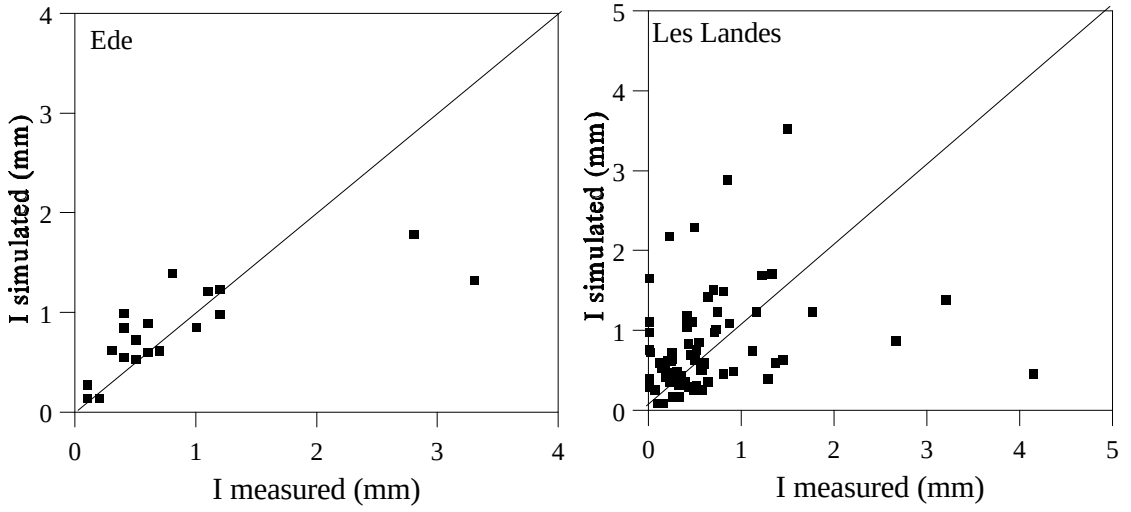

Figure 5.7. Simulated versus measured daily interception for Ede and Les Landes locations.

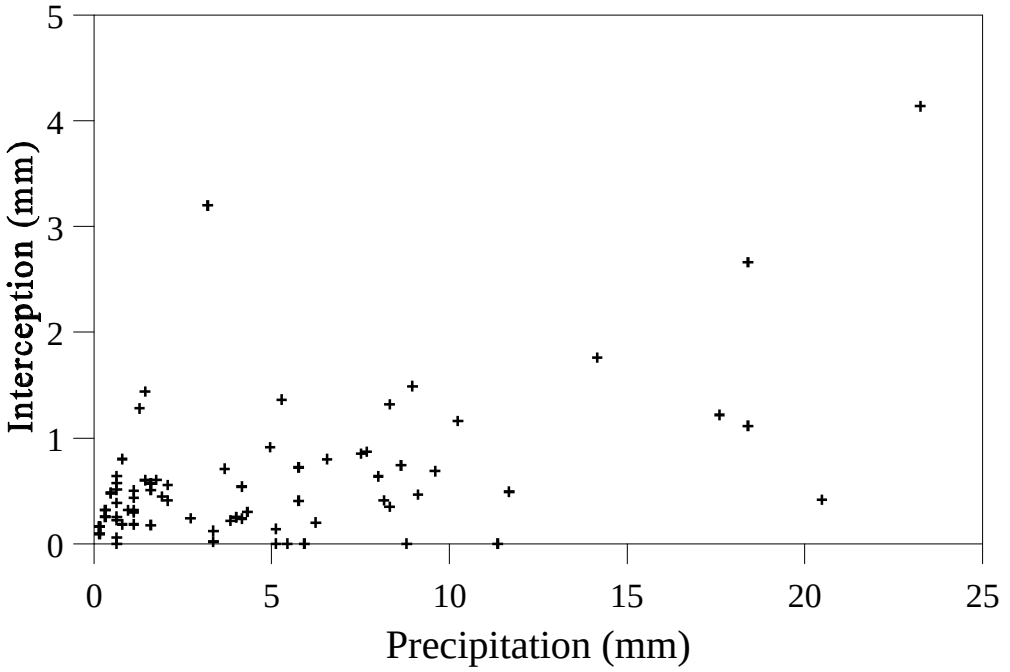

Figure 5.8. Interception versus precipitation for Les Landes location.

measured period in 1989 was 317.9 mm and interception 51.1 mm, the latter being equal to 16 % of the precipitation. The simulation was limited to 34 days, with a total of 92.9 mm rainfall. The measured cumulative interception was 20.4 mm versus 20.2 mm simulated (= 22 % of total rainfall, see figure 5.6). Plotting simulated versus measured daily amount of interception (figure 5.7), it is clear that the model generally overestimated the interception, except for the two large storms. The standard error (SE) of the simulated interception was 0.44 mm and *r* was 0.78, and 61 % of the variation in the interception could be explained by the model.

HAPEX-Les Landes

The measured daily totals of interception versus precipitation are shown in figure 5.8. The remarkable high spreading suggests a high accidental error in the measurements. Total precipitation over the measurement period of 85 rainy days was 369.9 mm and interception was 46.3 mm (equal to 12.5 % of total rainfall). The simulation model resulted in 60.8 mm interception, an overestimation of 14.5 mm (figure 5.9). The large difference between simulated and measured interception was confirmed in figure 5.7: the SE was large 0.78 mm, and *r*, the correlation coefficient was only 0.31. Only 9 % of the variation in the interception was explained by the model.

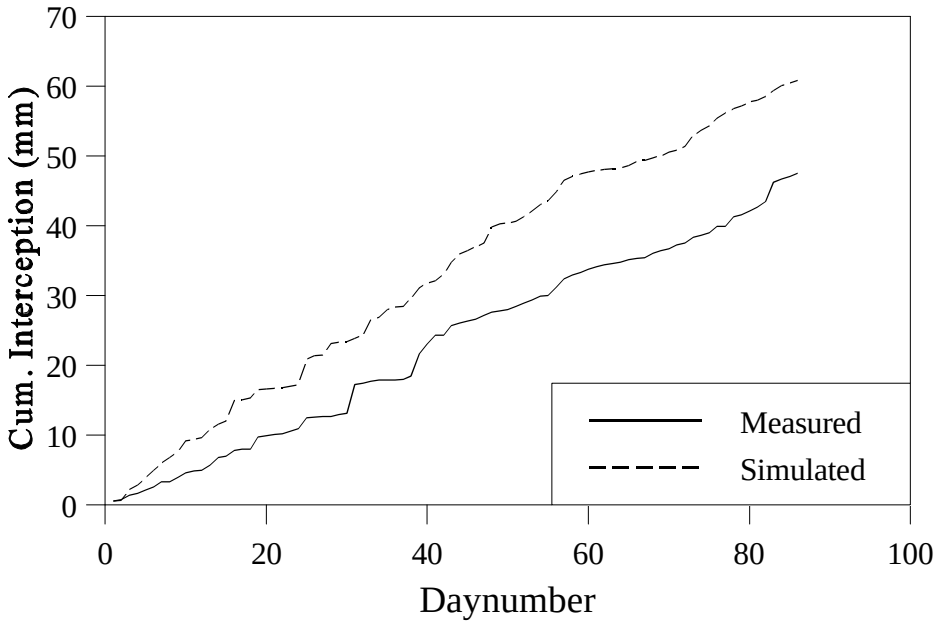

Figure 5.9. Accumulated measured and simulated interception for the Les Landes location.

5.2.4 Discussion of rainfall interception

The simulation of the interception at the Ede location was much better than at Les Landes: the model overestimates the rainfall interception during small storms and it underestimates the interception during large storms.

A possible explanation for the overestimation of rainfall interception (*I*), is an overestimation of the free throughfall coefficient *(p)* together with an overestimation of the average evaporation rate ($\bar{E}$). The underestimation of *I* at large storms can be explained by an underestimation of the storage capacity (*S*). In the simulation model, interception of small storms was strongly dependent on *p*, and 50 % of the storms were too small to saturate the canopy. Low value for $\bar{E}$ and a high value of *S* will result in an increase of *P*' and thus will lower the total interception of small storms, as the model was more sensitive to $\bar{E}$. In a former simulation study (Lankreijer *et al.*, 1993) a low $\bar{E}$ resulted in an improved agreement between measured and simulated interception. A further decrease of $\bar{E}$ would result in an even more accurate simulation, indicating, that a low value of the roughness length for latent heat ($z_{0,V}$) might be better, than the value, used in this study. Gash *et al*. (1995) also applied a reduced evaporation rate and an increased storage capacity, than calculated by the Penman equation and the Leyton analysis (Leyton *et al.*, 1967), respectively. Actually, they improved the model by a decrease of the estimated evaporation rate by multiplication of the evaporation with the fraction of the canopy, which covered the ground area. Multiplication of the estimated $\bar{E}$ by

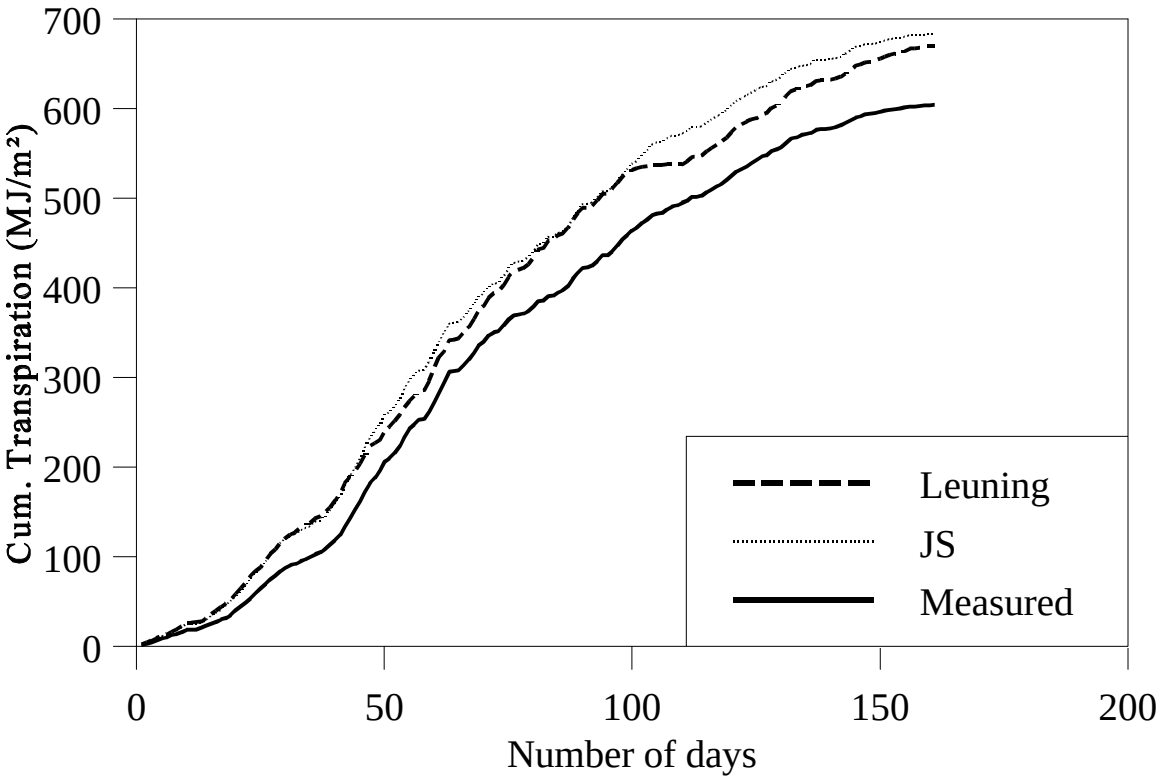

Figure 5.10. Cumulative transpiration measured vs simulated over complete data-set.

this ratio implies, that the advection of energy into the canopy and evaporation from open spaces in the canopy are left out of consideration. Reduction of the evaporation rate by the ratio of tree-cover to total area is questionable: the necessary reduction in $\bar{E}$ should preferably be found in a correct description of the canopy roughness characteristics within the Penman-Monteith simulation together with an improved description of the canopy storage capacity. An alternative explanation for the overestimation of $\bar{E}$ is, that an incorrect value for the roughness length of heat is used in the simulation. The value of $z_{0,M}$ is often directly related to the height of the forest (Shuttleworth, 1989; Gash, 1979; Dolman, 1986) and $z_{0,H}$ is assumed to be equal to $z_{0,M}$. If we suppose, that the tree density of a forest, the tree height and the leaf density of the canopy independently of each other affect the roughness length for heat and momentum and the zero plain displacement, a different value should be used for $z_{0,H}$. To overcome this problem in this study a relation, proposed by Garrat and Francey (1978), was used, notwithstanding the relation between $z_{0,M}$ and $z_{0,H}$ possibly is variable and not constant (Klaassen, 1996, pers. comm.). As also discussed in chapter 4, Lindroth (1993) found a value for $z_{0,V}$ close to $z_{0,M}$, when direct measurements of the vapour flux were used.

$\bar{E}$ was low, under conditions of low humidity deficit and a low value of the net radiation during storms. An overestimation of $\bar{E}$ might also be explained by the use of average hourly values, since dry periods during and after the storm may also be included in the data.

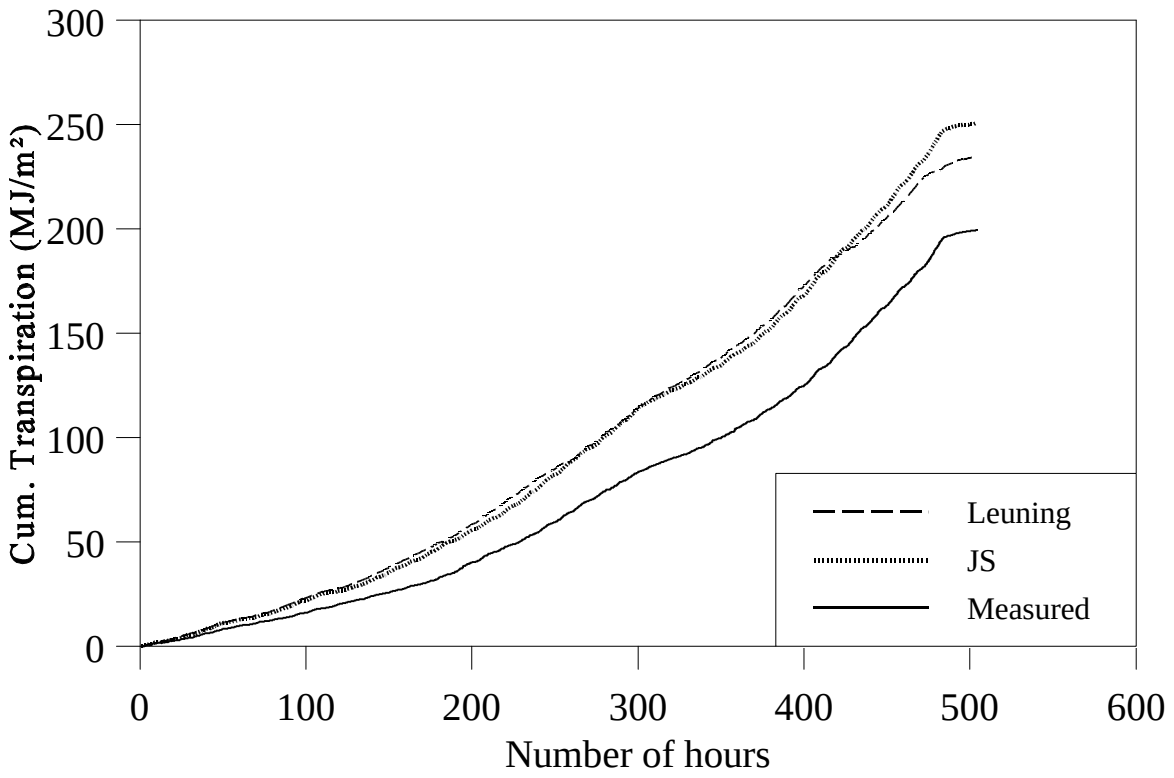

Figure 5.11. Cumulative transpiration of 504 hours with θ_D*< 80 mm.*

The incorrect simulation of the interception is further explained by an underestimation of *S*. Klaassen *et al.* (1996b) concluded, that the used analysis, following Leyton *et al.*(1967), might underestimate *S* by a factor of two. A higher estimation of *S* has been recently confirmed by Grelle *et al*. (1996). At the Les Landes location, errors in the measurements of the throughfall and precipitation also point to an underestimation of *S:* the spreading in the measured throughfall was high, as shown in figure 5.8. Even with a high precipitation, a low interception was found. Gash *et al.* (1995) obtained an error of 15 % in the estimation of interception, calculated as the difference between precipitation and throughfall. The value of *S* for Les Landes, 0.26 mm, was low, compared to other forests (Shuttleworth, 1989). A low value of *S* makes the model more sensitive to the evaporation rate. According to Klaassen *et al.* (1996b) the underestimated *S* compensated the overestimation of $\bar{E}$. The LAI of Les Landes forest was very small, and values and errors for *S* were small as well. Consequently, the error in $\bar{E}$ had more influence on the simulation exercise.

To improve the estimation of the rainfall interception one needs (*i*) an improved estimation of the roughness length for latent heat, (*ii*) an improved measurement of the canopy storage capacity, and (*iii*) a more careful treatment of the air humidity data during and directly after the storm (Klaassen *et al.*,1996b).

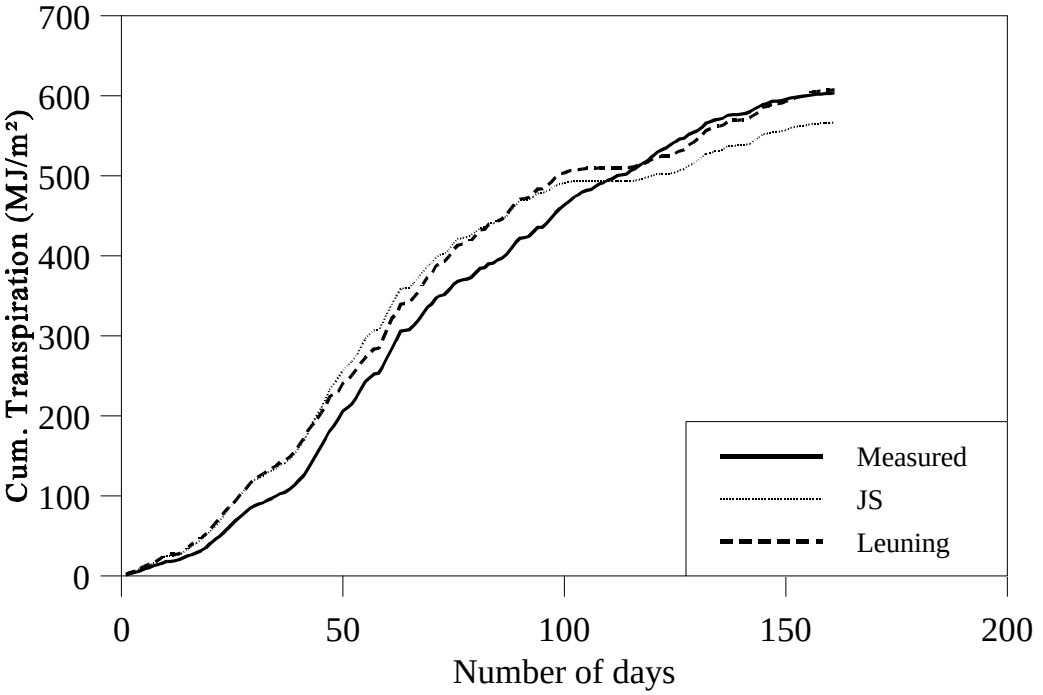

Figure 5.12. Cumulative transpiration over complete data-set with actual soil water content as input.

5.2.5 Simulation of transpiration

The Leuning- and JS-model versions of the simulation of transpiration overestimate the transpiration, as simulated on the complete data-set (figure 5.10). Total measured transpiration over the period was 604.1 MJ m^{-2} (= 246.2 mm) versus 683.3 MJ m^{-2} (=278.5 mm, +13 %) for the JS model and 669.3 MJ m^{-2} (= 272.7 mm, +11 %) for the Leuning version. Note, that the cumulative line of the JS simulation followed the measured line better than the Leuning version, except for the overestimation. It should be realized that only dry hours with available energy above 20 W m^{-2} were used for the comparison of transpiration results.

Comparison of the model results with actual measurements was limited to periods with ample soil water. The critical soil water content was set to 120 mm, based on the results by Ogink-Hendriks (1995). The cumulative results of the 504 selected hours are shown in figure 5.11. Both models overestimated the transpiration, with only a small difference between the models versions, even with the present limited data. The model calculated the daily soil moisture content, which deficit affects the stomatal conductance during the next day. In 1989 soil moisture content limited transpiration to a relatively large degree over a reasonable length of time. During this period, the availability of soil water influenced transpiration, which was at

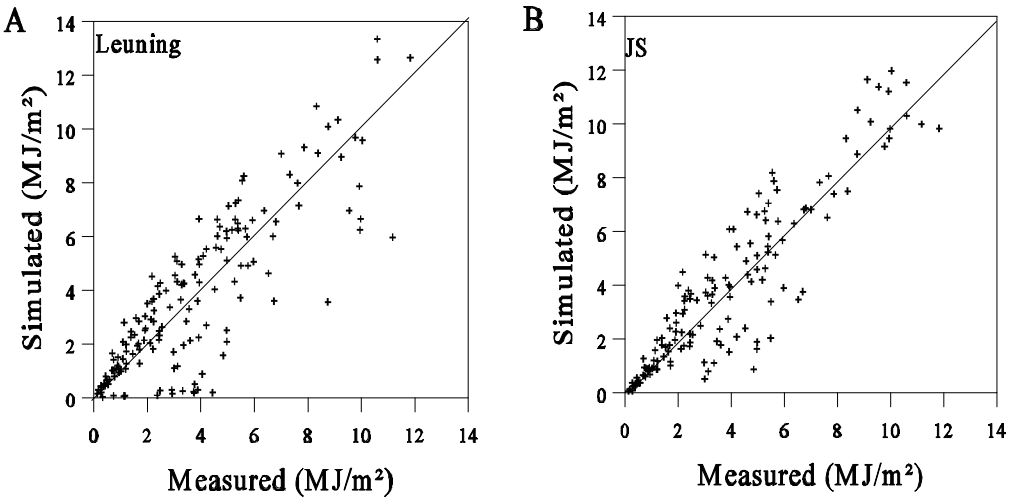

Figure 5.13. Measured versus simulated daily transpiration totals with use of actual soil water deficit as input.

the same time dependent on the interception simulation. Under those conditions, the daily values of simulated and actual measured transpiration could not be used for comparison.

To analyse the effect of soil water content on transpiration, the models were applied, using the measured soil water deficit (θ_D) as input. The models overestimated transpiration (figure 5.12) in the first half of the period, which overestimation was compensated by an underestimation in the second half period. The JS model resulted in a total of 567.0 MJ m^{-2} (equal to -6.1 %) and the Leuning-model in a total of 608.1 MJ m^{-2} (equal to +0.7 %). Plotting the daily measured totals versus the estimates of the transpiration, both models showed a large scatter(figure 5.13). The JS-model version was slightly better (r^2 = 0.93) than the Leuning-version (r^2 = 0.88).

The difference between both model versions is shown in more detail in figure 5.14: daily simulated transpiration was plotted versus the actual measured amount. Note, that figure 5.13

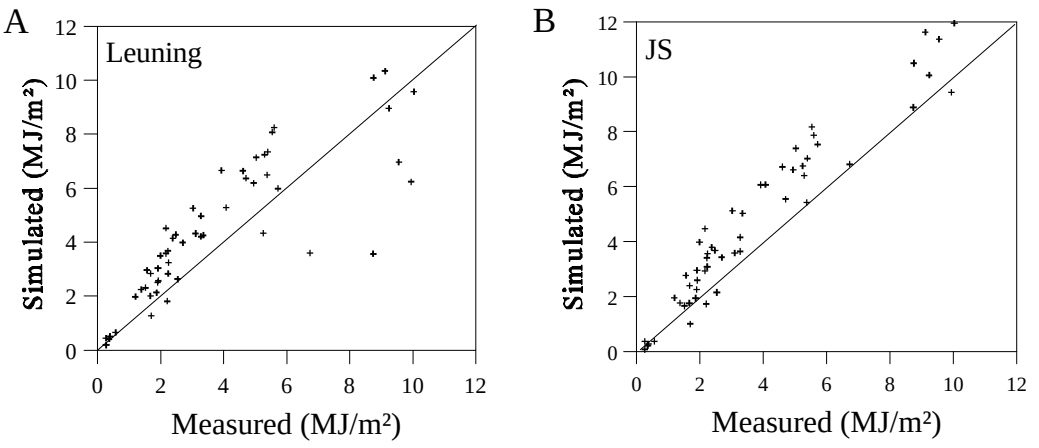

Figure 5.14. Measured vs. simulated daily totals of transpiration.

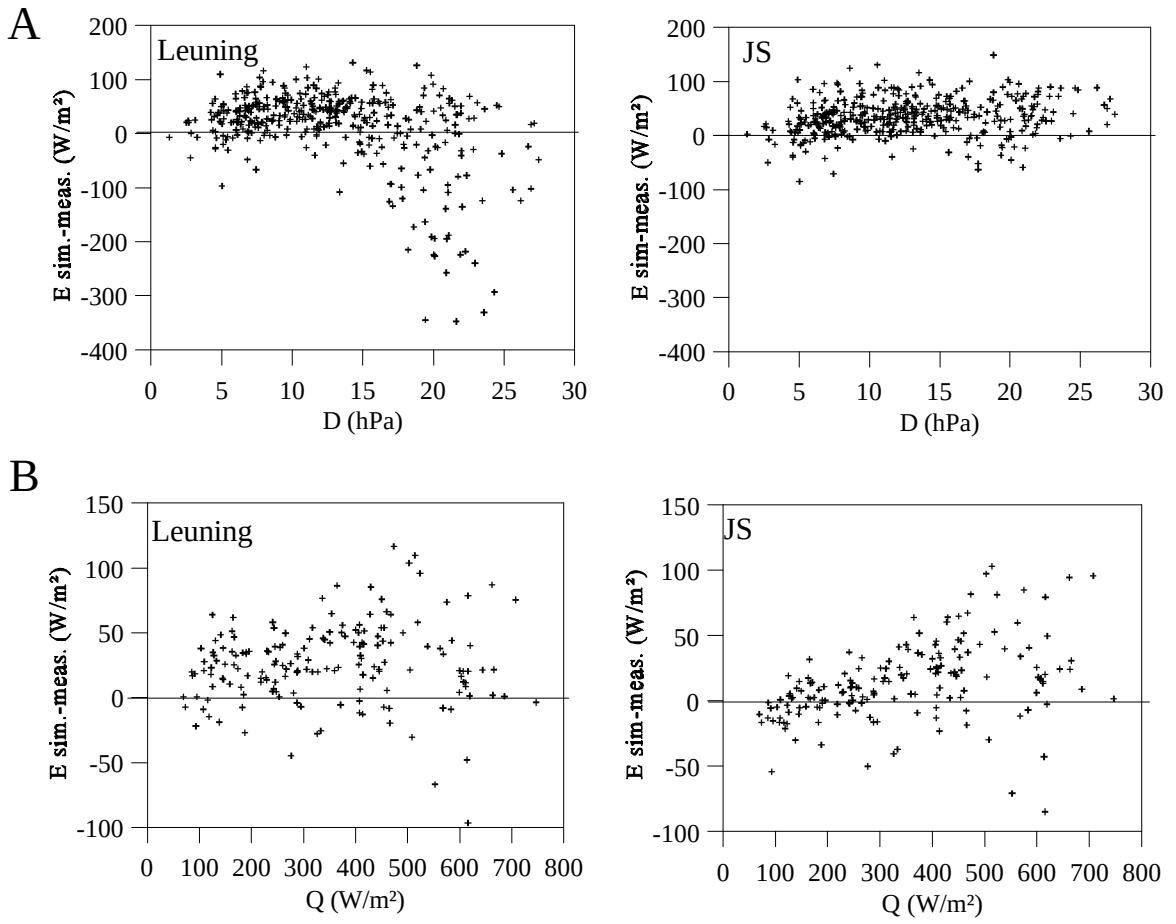

Figure 5.15. Comparison of simulated and measured hourly transpiration versus D and Q_s for left, the Leuning, and right, the JS model version. θ_D is smaller than 80 mm. Q_s > 250 W m^{-2} (A) and D < 8 hPa (B)

showed the daily totals of the simulation on the complete data-set, with the measured soil water deficit as input, while figure 5.14 showed simulation results without soil water deficit. The JS version frequently overestimated small values (n = 53, r^2 = 0.98), whereas the Leuning-model shows an overestimation with occasionally some remarkable underestimations (r^2 = 0.89).

The different simulation results of both models are shown in figure 5.15, where the difference between simulated E and measured E is plotted versus global radiation and air humidity deficit, respectively. In figure 5.15 A the hours with Q_s > 250 W m^{-2} were selected in order to exclude light limitation, and in the figure 5.15 B with Q_s the hours were selected for D < 8 hPa, in order to exclude limitation by air humidity deficit. When D was high, E_t, simulated with Leuning, was strongly underestimated in several, but not all cases. The overestimation of JS increased with global radiation, whereas in the Leuning-model overestimation was more spread over all values.

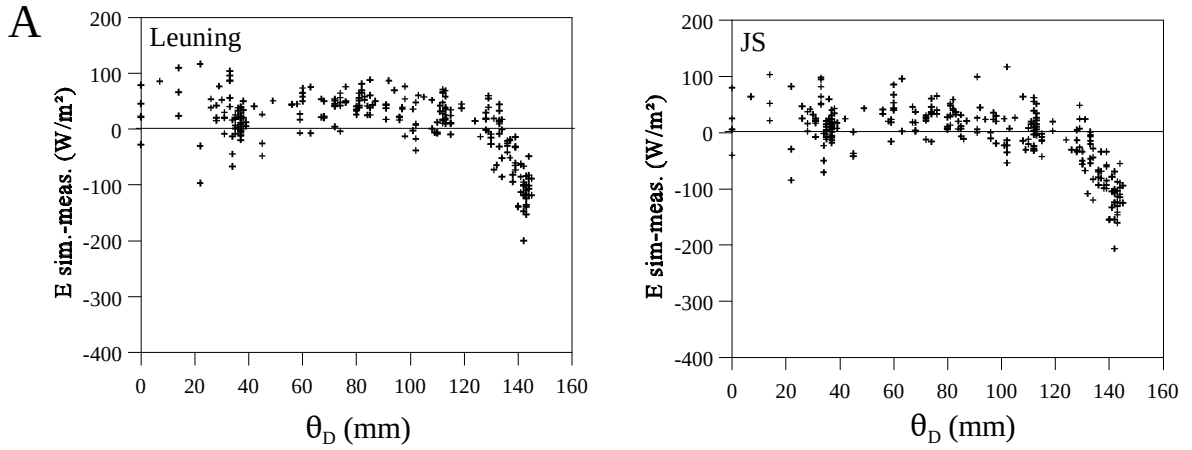

Figure 5.16. Comparison of simulated and measured transpiration versus actual measured θ_D

5.2.6 Discussion on simulation of transpiration

The overestimation of the transpiration by the JS-model over a large range of time and the consistent behaviour of the overestimation, seems to imply, that the $G_{s,\,max}$, used in the model, was too high. The JS-model was applied, using the fitted parameters of Ogink-Hendriks (1995). Also, the same data set was used. However, the discrepancy between the JS model and measured fluxes, and in contrast the satisfactory simulation results, found by Ogink-Hendriks (1995), may be attributed to the fact that a different selection of hours from the complete data-set was used in this study. Ogink-Hendriks selected hours, where the psychrometers were directed towards the wind, and in the present comparison, data were selected on the environmental conditions.

For the whole data-set the average JS simulation was quite well, but for parts of the year the fitted model was inadequate. The discrepancy between simulation and measured transpiration was explained by the used simulation models for soil water deficit and radiation. When soil water was not limiting (θ >120 mm), transpiration was overestimated, whereas with a soil water deficit (θ < 120 mm), transpiration was underestimated (figure 5.16).The model also overestimated transpiration in particular at high levels of radiation. The difference between the simulation results, using actual θ_D versus calculated θ_D, implies, that the applied soil water model was insufficient to simulate the water balance over a large range of time: the model simulated a higher soil water content, than was actual measured.

In some cases the Leuning-model application resulted in a strong underestimation of E_T at high D (figure 5.15 A), which is explained by the fact that under some circumstances leaf temperature strongly increased and caused the stomata to close. At low temperature and low transpiration there was no difference between simulated and measured transpiration, but at

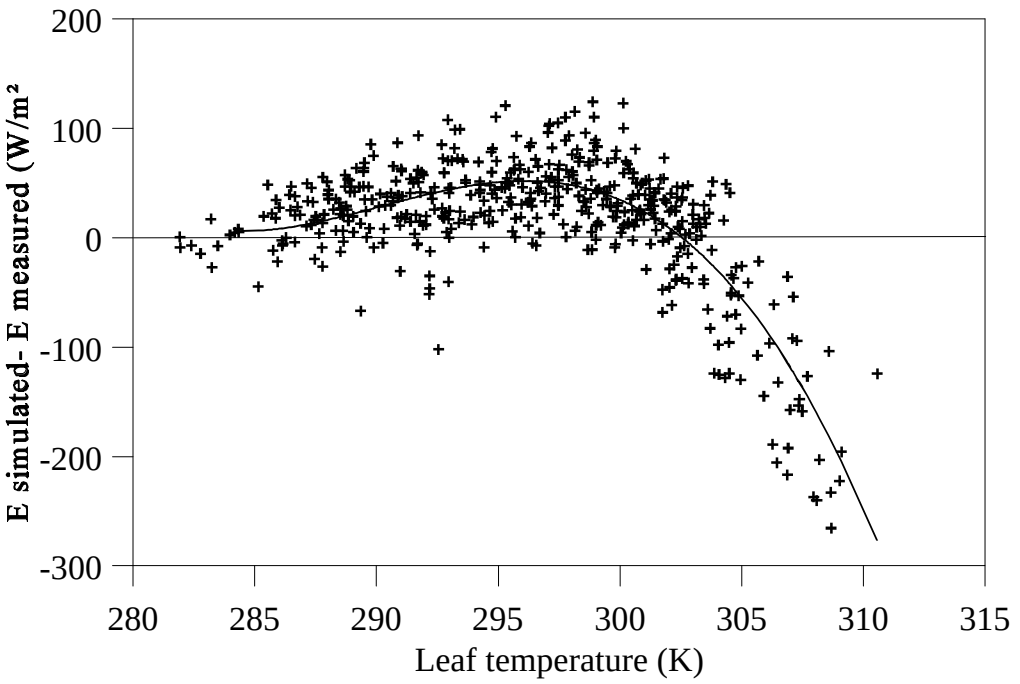

Figure 5.17. Leaf temperature vs. the difference between simulated and measured E_T. The line represents the average difference.

normal temperature, transpiration was overestimated, and at high temperature, strongly underestimated (figure 5.17). High leaf temperature resulted in low values for assimilation, stomatal conductance and transpiration. The low transpiration resulted in a further increase of T_L and D, together with increased heat flux and a further decrease of A. A low value of g was calculated at high D, when the aerodynamic conductance of the canopy was low, thus increasing the feedback mechanism. The JS-model does not have such a feedback mechanism, because a fixed function between G_s and the air temperature, instead of leaf temperature, is used.

The simulation with the Leuning-model might be improved by replacement of the Lohammar equation with the relation for humidity deficit, as applied by Ogink-Hendriks (1995). However, this replacement will not improve the physiological basis of the model: the latter might be improved by replacement of the g_s/D relation in the Leuning-model by the g/E relation, as proposed by Monteith (1995b). In the latter case the stomatal conductance will not be related to the air humidity deficit, but by the rate of transpiration, as was found by Mott and Parkhurst (1991).

In the application of the Leuning-model to simulate the transpiration, a constant ambient CO_2 concentration (C_a) was used. A constant C_a above canopy is realistic during daylight (Stewart, 1988; Gash *et al*., 1989), but it certainly is not valid inside the canopy; on a leaf scale a decrease in C_a can be expected during daylight. A lower C_a during daylight might result in an

increased stomatal conductance and consequently low C_a induced, increased transpiration.

Compared to the JS-model, the Leuning-model gives quite good results for simulation of transpiration. The results strongly depend on the fitted parameters a_1 and $D_{s,0}$. The variation in the stomatal conductance was simulated realistically, using the assimilation model of Farquhar *et al*. (1980) and the parameters settings of Friend (1995). The Leuning-model yielded good results, despite of the use of only two fitted parameters, a_1 and $D_{s,0}$, versus the 6 regression parameters used in the JS model. Taking into account the fact that for the application of the Leuning-model several parameters were assumed to be correct and constant in time, the simulation results might be further improved by optimisation, for example, by taking into consideration the *N*-content of the leaf. In the sensitivity analysis in section 5.3, the importance of the different parameters is further analysed.

5.3 Sensitivity analysis of the forest water balance model

A simple sensitivity analysis was performed on the forest water balance model, in order to evaluate the relative sensitivity of the forest water balance to the model parameters. The relative sensitivity of assimilation, transpiration and interception was expressed by introduction of a dimensionless index of sensitivity (β) for each of the tested parameters (Friend, 1995):

$$\beta = \frac{X_1 - X_0}{X_0} / \frac{P_1 - P_0}{P_0} \qquad (5.1)$$

where X_1 is the simulated value of respectively assimilation, transpiration and interception at the changed parameter P_1 and X_0 is the simulated value at the reference parameter value, P_0. A change in the parameter P will result in a directly proportional change in the simulated value X when $\beta = 1$.

The constants and variables, expressed in the model, were tested for the effect of a 10 % change in parameters. Some parameters, like the activation energy, are physical constants and therefore excluded from the sensitivity test. Parameters, which are linear related to other parameters or constants, were excluded as much as possible. For temperature (in K), a change of 10 % was unrealistic and the change in temperature was set to 1 %.

Tabel 5.6. Input values for the performance test of the Leuning model.

T_a	Q_s	u	h	LAI	N	C_a
20 °C	800 W m^{-2}	3 m s^{-1}	77 %	5	2 g m^{-2}	0.014 mol m^{-3}

The sensitivity analysis was performed for the assimilation and transpiration simulations, using one hour input data, in order to exclude the possible influence of long term soil water limitation and long term interception. The input variables were chosen from actual measurements under optimal conditions (table 5.5). Under the given light conditions, the assimilation rate was not limited by chloroplast electron transport and it depended on the amount of activated Rubisco, the CO_2 fixing enzyme, which will influence the sensitivity analysis. Consequently, parameters, determining $A_{c,}$ were taken into account and those of A_r were excluded.

The sensitivity parameter β for interception was determined for the complete data-set of Ede, 1989. The parameters of the interception simulation model were not influenced by other parameters, which change on the long run, but the sensitivity analysis will depend on the nature of the prevailing storms. The sub-model for the surface conductance, the Leuning-model, was separately tested for its performance, and input variables were changed over a realistic range, while other parameters were kept constant. The input variables solar radiation, Q_s, air temperature, T_a, ambient CO_2, C_a, air humidity deficit, D, and the physiological variables, *LAI*, and leaf nitrogen, N, (table 5.6) were varied versus the output variables A, G_c and R_d. The model was applied, with the use of the forest characteristics of the Ede forest location. Available energy (Q_{AC}) was calculated from solar radiation. The input data for the performance test were set to optimal values in stead of the optimal actual hours (table 5.5).

Tabel 5.5. Input values of one-hour sensitivity analysis for assimilation and transpiration.

T_a	Q_s	Q_n	u	H_s	h	LAI	C_a
20 °C	800 W m^{-2}	600 W m^{-2}	3 m s^{-1}	24 W m^{-2}	70 %	0.7	0.014 mol m^{-3}

5.3.1 Results of sensitivity analysis

Sensitivity analysis of simulation of assimilation and transpiration

The sensitivity values β for assimilation rate (A) and transpiration (E_T) are shown in figure 5.18 A and B. The assimilation rate is part of the transpiration simulation, and showed separately (figure 5.18 A). Assimilation was proportionally more sensitive to air temperature T_a, and parameters K_c and $_ok$, and to the energy maximum capacity of Rubisco, $V_{c,max}$ than transpiration: a small change in T_a would already strongly influence assimilation. Note, that,

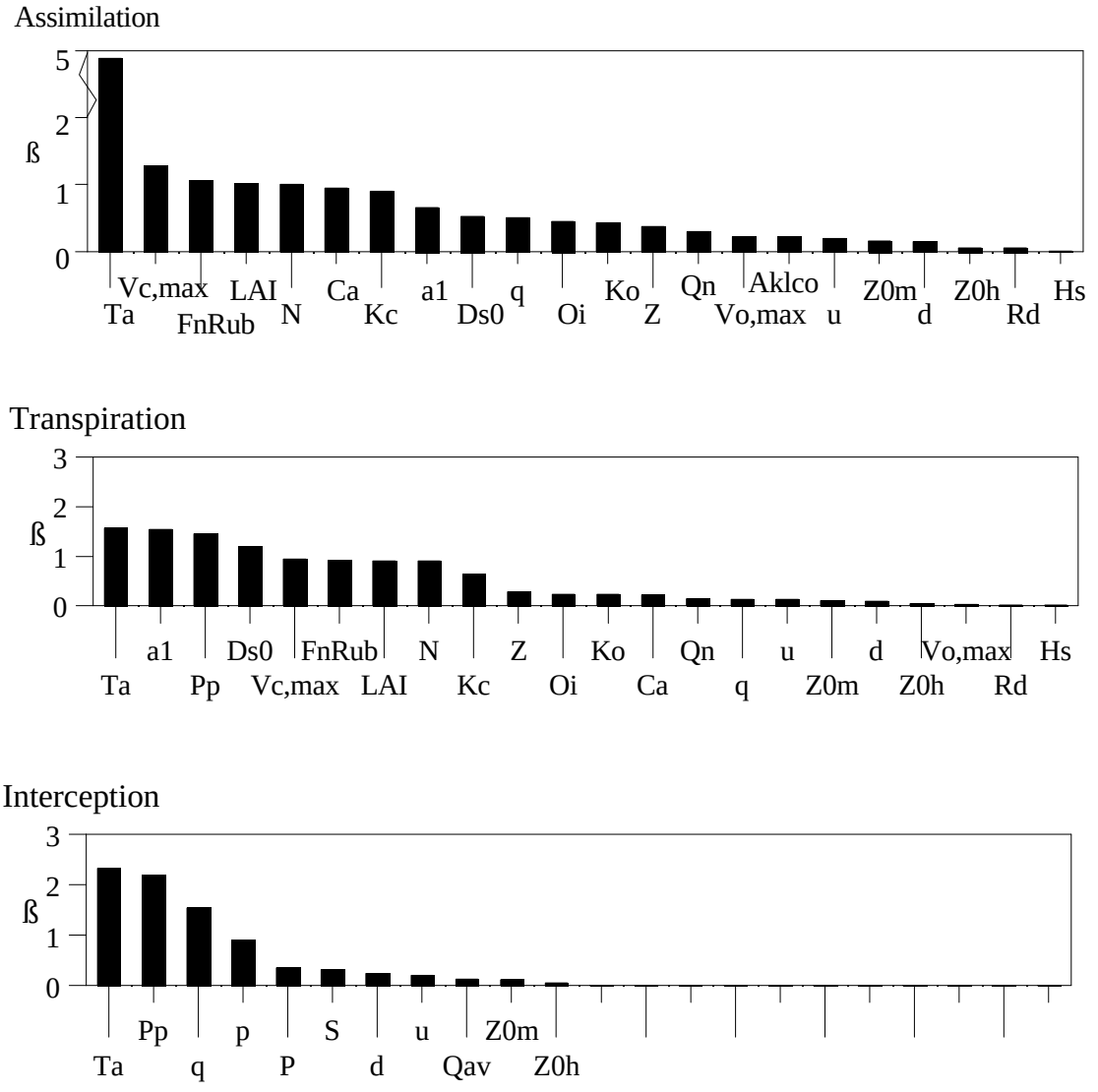

Figure 5.18. Sensitivity analysis of assimilation (A), transpiration (B) and rainfall interception (C). Note the difference in the y-axis in the figures.

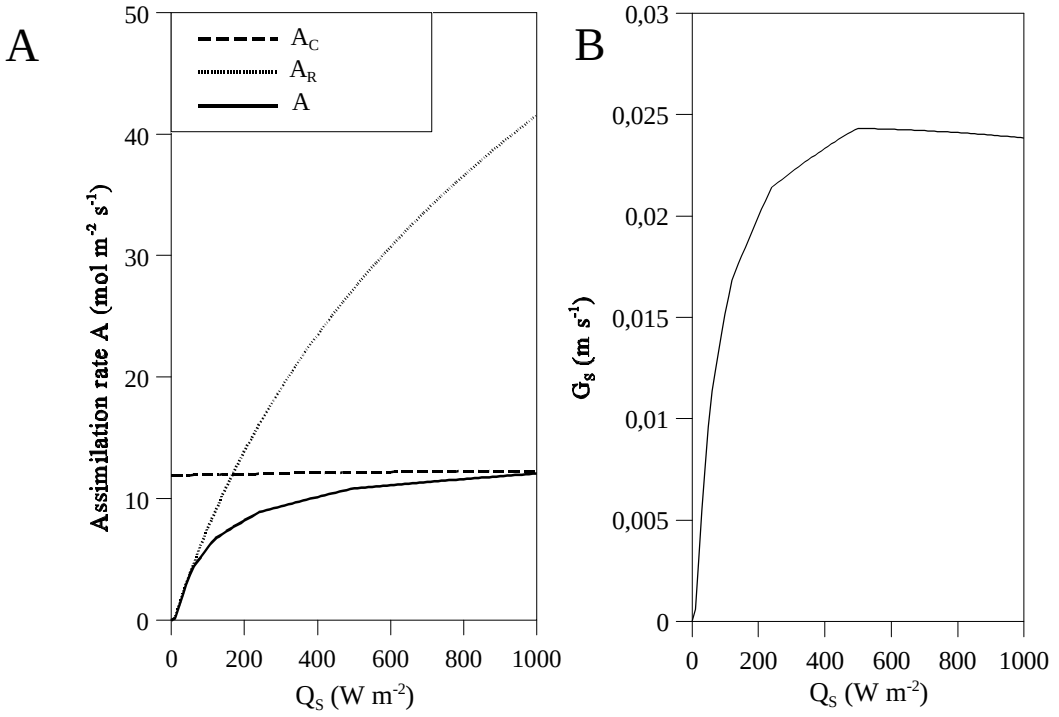

Figure 5.19A-B. Simulation of assimilation rate (A) and surface conductance (G_s) versus global radiation Q_s.

due to the use of the absolute temperature, a change of 1 % (≈3 K) was still remarkable, and resulted in a change of *A* of 5 %. The high sensitivity of *A* to leaf temperature, was due to the dependence of *A* to (temperature dependent) parameters K_c and k_c and the energy balance of the leaf. Assimilation was nearly proportional to the leaf area index, LAI, the nitrogen content of the leaf, *N*, and related fraction of nitrogen in Rubisco, $f_{N,Rub}$. A significant sensitivity of the assimilation was also obvious for the parameters a_1, $D_{s,0}$, and the ambient CO_2 concentration. The high sensitivity for LAI of both the assimilation and the transpiration is not in agreement with Kelliher *et al.* (1993, 1995), but is explained by the use of a low value for LAI as default setting.

Transpiration (figure 5.18 B) strongly depended on parameters, determining surface conductance and assimilation. The assimilation was proportional with G_s, but a low value of β for E_T versus air temperature was found. Temperature had a direct influence on *A* and, through *A* and Γ on the surface conductance G_s. But the change in stomatal conductance affected transpiration as well as heat flux of the leaf, resulting in a decreased sensitivity of the transpiration to a change in T_A. Besides, Ē depended also on air density, which was inversely proportional to T_A. The same observation is valid for the sensitivity of transpiration for air humidity *q*: assimilation was more directly determined by the humidity then transpiration and can be attributed to the scaling settings in the model. The effect of humidity and temperature on *A* was calculated on a leaf scale, with the use of the leaf temperature, as found in the

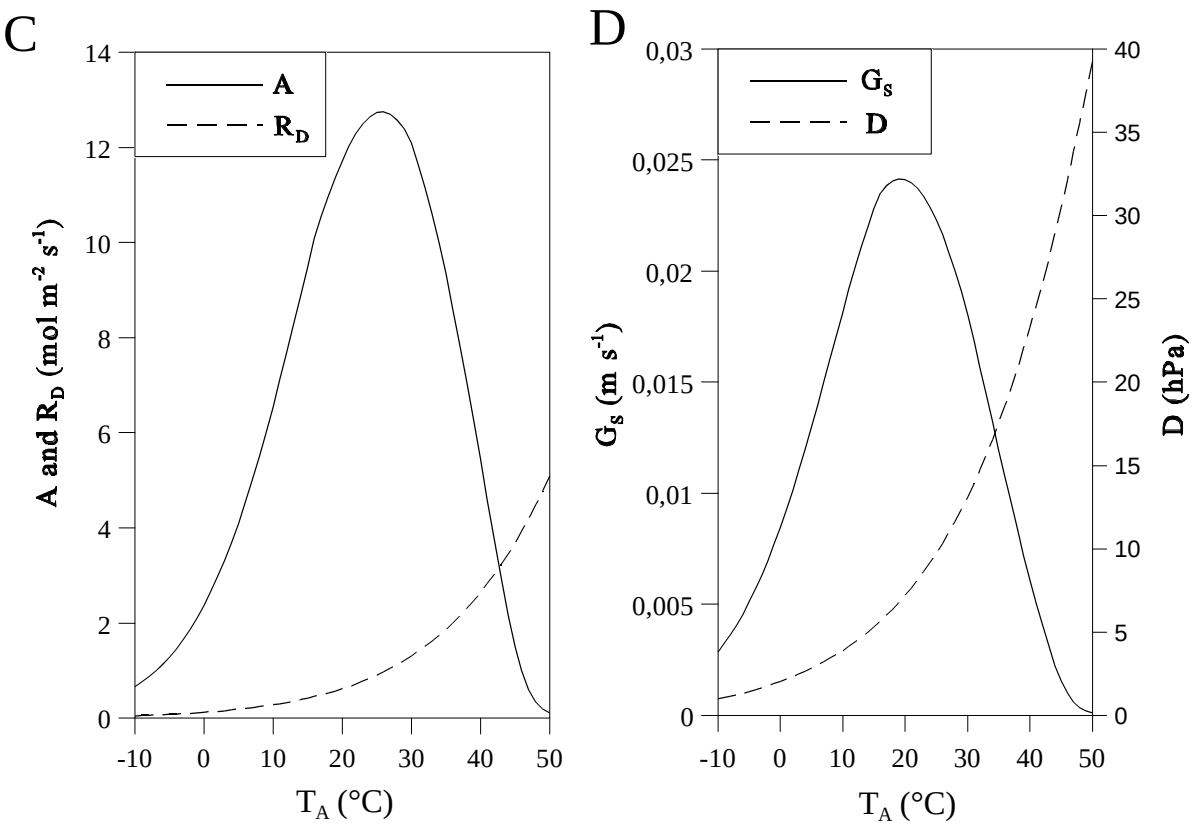

Figure 5.19C-D. Assimilation rate and surface conductance versus air temperature

iterative process. Total transpiration was calculated for the whole canopy and the humidity deficit was calculated from above canopy conditions.

Transpiration was highly sensitive to air pressure *P*, which sensitivity was caused by the use of specific humidity as an input variable (g kg^{-1}). In this form the air pressure determines the mass of air, actual present, as well as the amount of water vapour present. A 10 % change was equal to a change of 101 hPa, which was large and unrealistic.

The responses of surface conductance and assimilation rate were also derived from the performance test (figure 5.19, A-H).

At a low radiation level, the assimilation rate of the canopy was limited by A_r, which is the assimilation rate limited by regeneration of RuBP (figure 5.19 A). Different radiation levels were present in the canopy, and therefore the canopy assimilation gradually reached a maximum value. The Rubisco content of the leaf mainly determined the level of *A* for $Q_s > 200$ W m^{-2}. Stomatal conductance reached a maximum value at intermediate radiation values (figure 5.19 B). At high radiation levels, G_s was slightly decreased, which was caused by a feedback with increased leaf temperature, T_L: the latter increased with irradiation, and consequently *A* decreased and G_c only slightly decreased.

In figure 5.19 C and 5.19 D the relative humidity *h* was kept constant with T_A. Humidity deficit (*D*), as given in figure 5.19 D, increased with temperature, affecting both *A* and G_s. *A*

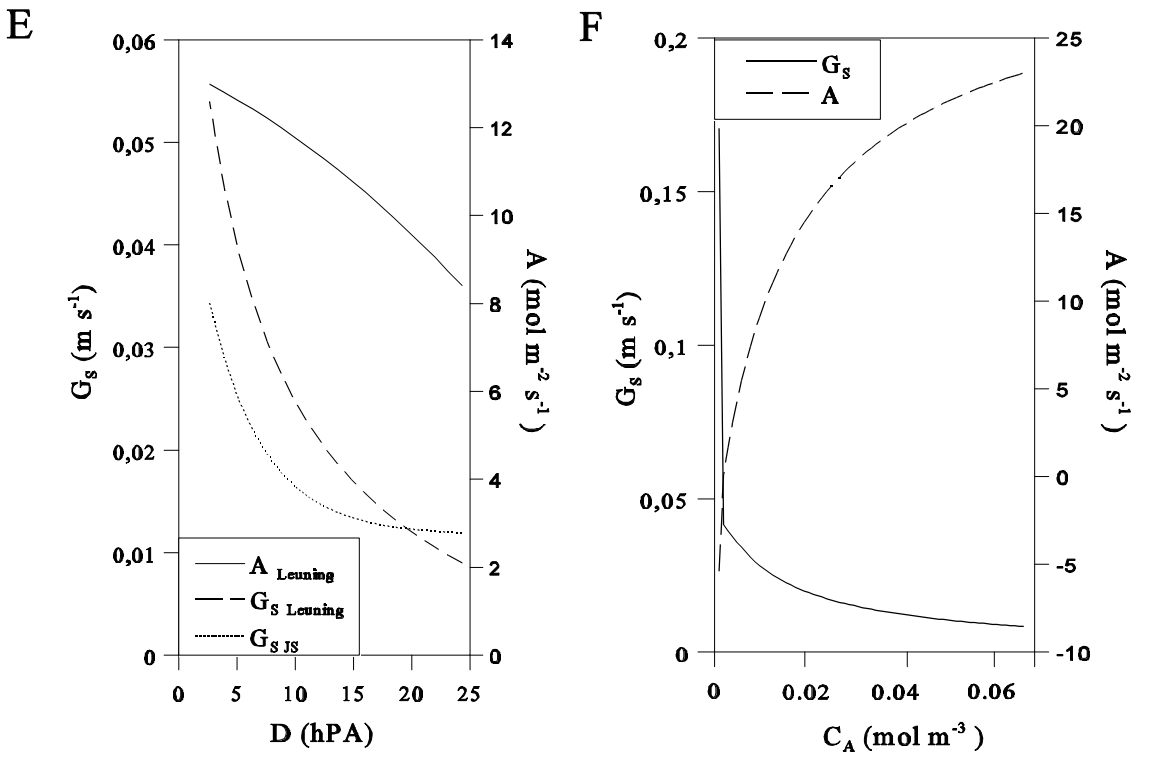

Figure 5.19E-F. Assimilation rate and surface conductance versus air humidity deficit and ambient CO_2.

was also limited by increasing respiration rate (R_d) with temperature, but the respiration rate exceeded assimilation only at temperatures above 40 °C. The optimum temperature for G_c was around 18°C, in agreement with the value found by Ogink-Hendriks (1995) for the Ede forest location. The maximum *A* is found for a slightly higher temperature than that of G_s, which can be attributed to the following effect of the leaf temperature. The stomatal conductance was limited by the humidity deficit, due to an increased leaf temperature, while at the same time *A* still increased with leaf temperature. The low stomatal conductance caused a high value of T_L, which caused a further decrease in conductance, and at the same time an increase in *A*. At high temperatures, *A* was limited by the stomatal conductance, causing a low CO_2 availability inside the leaf. The difference of optimal temperature for assimilation and transpiration could explain the difference in sensitivity of transpiration and assimilation for temperature (figure 5.19 A, B), due to an optimum G_s at 20 °C, the temperature used in the sensitivity study.

In figure 5.19 E the sensitivity of G_s is shown versus *D*. The function, used in the Leuning version and the JS-versions are shown together with the performance of *A*. Compared to the fitted regression function of JS by Ogink-Hendriks (1995), the Leuning function overestimated the surface conductance over a larger range of *D*. The simulated G_s reached a

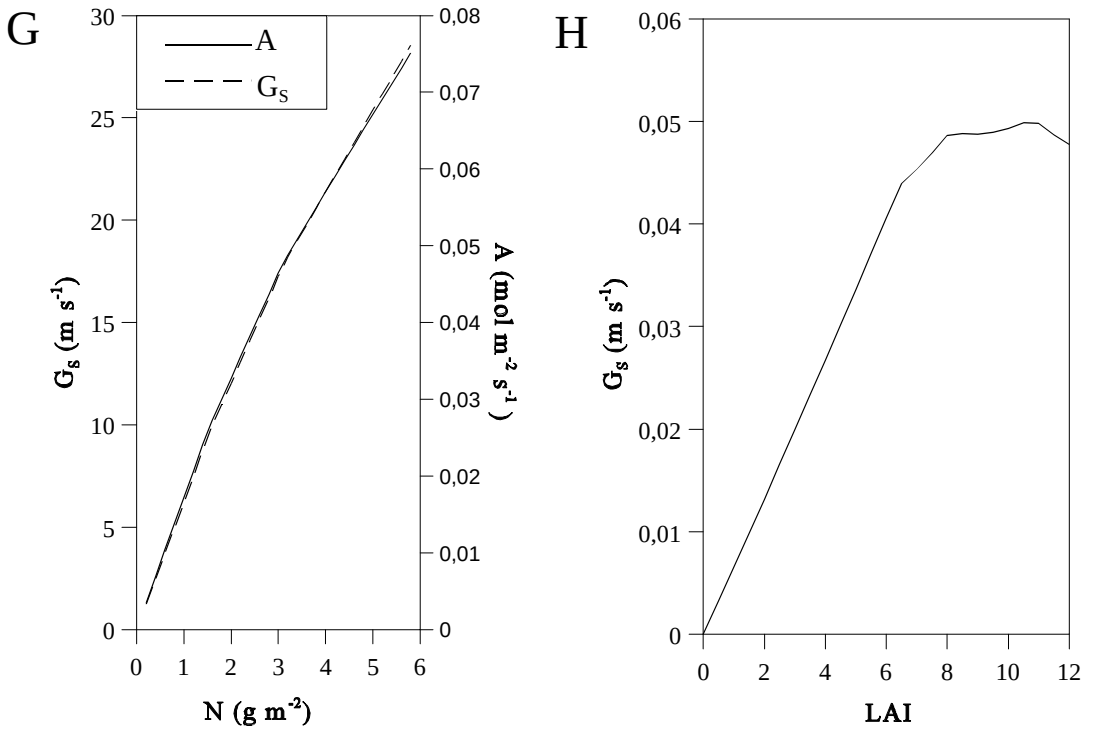

Figure 5.19 G-H. Assimilation rate (A) and canopy conductance (G_s) versus nitrogen content of the leaf and LAI.

minimum value in the JS model, but G_s still decreased in the Leuning-model.

As shown in figure 5.19 F the decrease of G_s with increasing ambient CO_2 was strong at low values of C_a, but on overall a gradual decrease was observed. Doubling of the actual CO_2 concentration from about 317 ppm to 634 ppm decreased G_s about 30 %, using the Leuning-model, which is in agreement with Morison (1987).

The high sensitivity of both G_s and A to the nitrogen content of the leaf is clearly evident from figure 5.19 G, which sensitivity makes the setting of the *N*-content in the simulation model a crucial parameter, if we consider the possible changes in *N*-content in leaf and soil with a climate change.

Surface conductance increased up to a LAI of about 8 and above this value the surface conductance did not increase and became irregular (figure 5.19 H). The increase in LAI caused a decrease of light intensity, deeper into the canopy, and no further increase in G_s with LAI was observed. The observed irregularity suggests, that the values of parameters as regression parameters and Rubisco concentration, needed adaptations to high LAI characteristics, for example by changing the characteristics of Rubisco content and absorption coefficient, in the deeper layers in the canopy.

Sensitivity analysis of simulation of rainfall interception

The sensitivity analysis of rainfall interception strongly depended on the input data: it was determined by the ratio of the number of storms, which were large enough to saturate the canopy, and the number of storms, which did not saturate the canopy.

The β values of interception and transpiration in figure 5.18 are hazardous to compare, because of the use of different data sets in the sensitivity analysis. Nevertheless, the interception showed also a strong sensitivity for air pressure. The reason for this sensitivity is the same as already described for transpiration: the use of specific humidity. The sensitivity of rainfall interception to T_a and q was high, which can be attributed to an increase in humidity deficit during a storm, indicating, that the storms, which saturate the canopy had an important affect on the sensitivity of interception: D can be expected to be low under normal circumstances during rainfall, but it will increase the sensitivity with increasing temperature. On the other hand, an increase in q lowered the rainfall interception, because D decreased.

The sensitivity of interception to precipitation *(P)* can be explained by the change in the number of storms, saturating the canopy. When the number of small storms - too small to saturate the canopy - was relatively large, the rainfall interception was more sensitive to a change in P. When the canopy was already saturated, a change in total precipitation had less or no effect on the rainfall interception. The model calculated the rainfall interception on daily totals and it left out of consideration the sensitivity to the number of storms. An increase of the number or the duration of the storms will affect both total rainfall interception and transpiration, since the canopy will be wet for a long period.

5.3.2 Discussion on the sensitivity analysis

The optimal environmental conditions for the sensitivity analysis, strongly influence the results. Different values of optimal environmental conditions for input can alter the β value, and partly the sequence in sensitivity of the studied parameters.

Clearly, transpiration is highly sensitive to physiological characteristics of the vegetation, and the leaf-related parameters influence the transpiration on a canopy scale, as well. Most important parameters in this respect are, T_L, $V_{c,max}$, LAI and, especially the nitrogen content of the leaf. Also, the regression parameters a_1 and $D_{s,0}$ are influential in the estimation of transpiration and assimilation. The exact meaning of those parameters is still a black box, but Dewar (1995) already showed (as described in chapter 3) the physiological character of the parameters. The use of $D_{s,0}$ can be avoided by application of the g_s/E relation, as proposed by

Monteith (1995).

Rainfall storage capacity of the canopy (*S*), and, more important, the free throughfall coefficient (*p*) influence the amount of rainfall interception. When the storms are small and shortly after each other, the total interception will be determined by the free throughfall coefficient, and to a lesser extent, the evaporation rate, which is an artefact of the model input. The total number of storms in the test run on interception was 78 with a total of 283.53 mm rainfall and 42.55 mm interception. The number of storms, where the canopy was not saturated, was 42, a little more (54 %) than the half of the total storms directly dependent on *p*. Sensitivity of interception to *p* will also depend on the value of the *p*, as interception scales up with the factor (1-*p*). A fixed and fractional change in a small *p* value, will only have a small effect on the interception within a dense canopy. Changes in a large *p* will strongly change the interception of an open canopy. The value of *p* for the deciduous Ede forest was low during the summer, and high during winter, resulting in a small effect of a change in *p* in summer and a large one in winter. The tests on *S* and *p*, however, were not complete, because the missing relationships of *S* and *p* with LAI and the canopy structure. The model and sensitivity analysis would be improved, if an empirical relation was used in which LAI was included to describe the effects of *S* and *p*. So far, too limited research has been performed to give reliable relationships between these parameters.

Forest water balance

The expected climate change in temperature will have a large affect on transpiration and rainfall interception, the latter also being determined by the air humidity. Important factors for transpiration are the availability of nitrogen for leaf growth and acclimatisation of the (increased) photosynthesis of the leaves. When soil water availability is limited, an increase in the rainfall interception will decrease the throughfall and it will affect assimilation and transpiration of the canopy. In the model the influence of the topsoil was left out of consideration. In this respect the occurrence of a (thick) litter layer is important for the forest hydrology: a decrease in interception by the canopy, will increase the interception of the litter layer, and limit the net affect on soil water recharge. On the other hand, the litter layer will keep soil evaporation low.

The effects of an increase of atmospheric CO_2 and consequent a climate change on transpiration of forests are strongly species dependent. The stomatal conductance of several tree species, especially coniferous, shows no response to an elevated level of atmospheric CO_2 (Eamus and Jarvis, 1989). Canopy growth of these species might increase, but the extent of the growth increase will depend on light interception and available mineral nutrients. If we assume

that canopies of forest ecosystems are already optimal in relation to the available light, the subsequent increase in LAI by elevated CO_2 will be small.

5.4 Conclusion

The applied model for assimilation, transpiration and rainfall interception was a simple and rather incomplete representation of the processes, which determine the water balance of a forest. Nevertheless, the simulation results are promising: the Leuning-model, incorporated into the forest water balance model, realistically simulated the response of the stomatal conductance to environmental and plant parameters. It was sufficiently reliable to make the extrapolation to climate changed conditions valuable.

Compared to the JS model, the Leuning model version simulated transpiration well, considering the high number of parameters in the assimilation model. The relationship between the stomatal conductance and several of the environmental parameters, was realistically simulated. The large error in the simulation could be mainly attributed to an incomplete description of the heat balance of the canopy and the temperature at a leaf scale. The simulation of the leaf temperature and heat balance, including the CO_2 and H_2O transport resistance formulation, still needs further improvement. The overestimation of the transpiration by the Leuning-model was partly explained by the relatively high value of G_s at moderate D, as compared to the regression model of JS. This problem, as mentioned before, might be solved by application of the relationship between g_s and E from Monteith (1995b). Also, the soil water simulation model needs further improvement. To include the Leuning-model in ecosystem simulation models, parameters, determining the level of the assimilation and stomatal conductance, as well as the nitrogen content and the photosynthetic capacity of the leaves of the canopy, needs further tuning in order to arrive at reliable simulations of a climate change.

A regression model type, like JS, is clearly data-dependent. Values of the regression parameters were determined by the data-set and were poorly transferable to other forest types, locations or even to other times. The Leuning-model also contains several forest and species dependent parameters, but nevertheless this type of model is preferable in the assessment of effects of environmental or plant-specific responses to climate change.

Changes in temperature and ambient CO_2 concentration are the most important parameters if we consider the effect of a climate change on the water balance of forests, and they cause opposite responses. In the long run, response of forests to the temperature change may be stronger. From the present sensitivity study we conclude, that the water use of forests depends

on parameters as leaf area index (LAI), the nitrogen content (*N*) and photosynthetic capacity of the canopy leaves. Note, that *N* influences the LAI and photosynthetic capacity. Under normal conditions the C/N ratio in the leaf increases, when CO_2 uptake increases and *N*-uptake remains unaffected. The low *N*-content in the leaf in its turn, will on the long term decrease the assimilation augmentation by temperature, and leaf and canopy transpiration will decrease. However, due to *N* deposition, the *C/N* ratio of the forest leaves might remain constant and consequently transpiration might increase to a certain extension, which extension will depend on the availability of nutrients as phosphor, and water availability.